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OBSERVATIONS ON THE GENERALITY OF THE GRAIN-SIZE EFFECT ON FATI--ETC(U)
MAY 80   G R YODER, L A COOLEY, T W CROOKER
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Results obtained through analysis of the literature agree with those of our own as regards the effect of grain size (ℓ) on region-II fatigue crack growth rates (da/dN) of $\alpha+\beta$ titanium alloys in ambient air, viz. that for a given value of stress-intensity range (ΔK), da/dN decreases as ℓ is increased. The analysis indicates that when microstructural modification of a given alloy affects a reduction in da/dN, the reduction appears attributable to an increase in ℓ; conversely, when microstructural modification fails to affect a significant change in da/dN, the result appears attributable to a negligible change in ℓ. Comparison of fatigue crack growth behavior at stress-intensity ranges of

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20. Abstract (Continued)

15, 21 and 40 MPa$\sqrt{m}$ indicates a diminution of the grain-size effect with increased ΔK. As elucidated in terms of the reversed plastic zone size model, diminution of the grain-size effect follows as a consequence of the reduced portion of the structure-sensitive mode of crack growth present as ΔK is increased.

CONTENTS

OBSERVATIONS ON THE GENERALITY OF THE GRAIN-SIZE EFFECT ON FATIGUE CRACK GROWTH IN $\alpha + \beta$ TITANIUM ALLOYS

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Introduction

Within the past decade, significant interest has been focused on the influence of microstructure on region-II fatigue crack growth rates (da/dN) in $\alpha + \beta$ titanium alloys. Though it has been demonstrated conclusively that growth rates in air can be markedly reduced through microstructural modification, an elucidation of the principles for this microstructural dependence has remained elusive. Recently, however, a breakthrough on this subject was offered from a study conducted with a wide range of $\alpha + \beta$ alloys, of varied microstructural types and chemistries [1]. In particular, it was reported that da/dN decreases systematically with increased grain size ($\bar{\ell}$). In that work, a 50-fold decrease in da/dN was observed for a 15-fold increase in $\bar{\ell}$, at a stress-intensity range (ΔK) of 21 MPa$\sqrt{m}$. A model for this effect was offered in terms of reversed plastic zone size considerations [1,2].

The purpose of this paper is to comparatively analyze the results of several other investigators [3-14], in an effort to critically assess the generality of grain-size influence on region-II crack growth rates. To this end, work has been analyzed from the major microstructural studies of Thompson, Williams, Frandsen, and Chesnutt [10], Eylon and Pierce [5], and Amateau, Hanna, and Kendall [3] among others. For this analysis, significantly different levels of stress-intensity range have been selected, viz. ΔK = 15, 21, and 40 MPa$\sqrt{m}$.

Survey and Analysis

The materials surveyed from references [3-14] are identified in Table 1 according to alloy system, interstitial oxygen content, yield strength and heat treatment (mill anneal, MA; recrystallization anneal, RA; beta anneal, BA; duplex anneal, DA; solution treat + age, STA; or solution treat + overage, STOA). To the extent feasible, values of da/dN have been estimated for each material at the three levels of ΔK selected for comparison. In all cases, only region-II growth rate behavior is considered, even though such behavior appears generally to be bilinear in form -- a point to be discussed subsequently. As indicated in the table, the stress ratio (R) is about the same in most instances. Also from each reference, values of $\bar{\ell}$ have been estimated for each microstructure from the available photomicrographs. Since the α-phase predominates in the microstructures of these $\alpha + \beta$ alloys, estimates of $\bar{\ell}$ relate to the size of the primary α-phase (or the colony size, which is the effective grain size in the case of the Widmanstätten morphology [15]).

Comparison of fatigue crack growth rates for the different materials is made in Figs. 1-3 at the respective levels of ΔK = 15, 21 and 40 MPa$\sqrt{m}$. In each figure, da/dN is plotted in semilogarithmic form as a function of $\bar{\ell}$, with solid symbols used to denote materials from Table 1 and open symbols to indicate our own data, cf. reference [1]. Symbol shape is used to identify the heat-treated condition of each material; in the case of each solid symbol, a companion reference number can be used to identify the material according to Table 1. It is appropriate to note that these figures each contain

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Table I — Identification of Materials

Ref	Symbol (cf. Fig. 1)	Alloy System	Heat Treat.	R	σ_y (MPa)	O (wt pct)	Orientation	Investigators
3	▼	Ti-6Al-6V-2Sn	MA	0.10	1095	–	TL	Amateau, Hanna & Kendall
	●	Ti-6Al-6V-2Sn	DA	0.10	1038	–	TL	Amateau, Hanna & Kendall
	▲	Ti-6Al-6V-2Sn	BA	0.10	964	–	TL	Amateau, Hanna & Kendall
4	▼	Ti-6Al-6V-2Sn	MA	0.10	1100	0.19	TL	Dawson & Pelloux
5	●	Ti-6Al-4V	DA	0.10	887	0.16	LT	Eylon & Pierce
	◀	Ti-6Al-4V	STA	0.10	896	0.16	LT	Eylon & Pierce
	▼	Ti-6Al-4V	MA	0.10	880	0.16	LT	Eylon & Pierce
	●	Ti-6Al-4V	RA	0.10	843	0.16	LT	Eylon & Pierce
6	▲	Ti-6Al-4V	BA	0.05	1029	0.12	TL	FitzGerald & Wei
7	●	Ti-6Al-4V	RA	0.30	834	0.12	LT	Harrigan, Kaplan & Sommer
	●	Ti-6Al-4V	RA	0.30	924	0.20	LT	Harrigan, Kaplan & Sommer
8	●	Ti-6Al-4V	DA	0.10	945	0.18	TL	Lewis & Crossley
9	▲	Ti-6Al-4V	BA	0.05	852	0.12	TL	Spurr, Boyer, Bajoraitis & Engdahl
10	▶	Ti-6Al-4V	STOA	0.10	908	0.12	PAN. FGNG.	Thompson, Williams, Frandsen & Chesnutt
	●	Ti-6Al-4V	RA	0.10	707	0.12	PAN. FGNG.	Thompson, Williams, Frandsen & Chesnutt
	▲	Ti-6Al-4V	BA	0.10	774	0.12	PAN. FGNG.	Thompson, Williams, Frandsen & Chesnutt
11	●	Ti-6Al-4V	RA	0.10	830	0.11	LT	Tobler
12	▼	IMI-318	MA	0.10	1063	–	TL	Wanhill
13	▼	Ti-6Al-4V	MA	0.10	960	0.14	TL	Wanhill & Döker
14	◀	Ti-6Al-4V	STA	0.10	916	0.18	PAN. FGNG.	Yuen, Hopkins, Leverant & Rau

different numbers of data points, owing to differences in the spectra of ΔK for which growth-rate data were obtained by different investigators, as well as the fact that in several instances a ΔK level of 40 MPa$\sqrt{m}$ exceeds the limits of region-II fatigue crack growth behavior.

Examination of these figures indicates three major points. First of all, at each level of ΔK, the compendium of data confirms that da/dN decreases as $\bar{l}$ is increased. Clearly, the data from references [3-14] are in reasonable agreement with each other (as well as with our own data). In fact, the degree of agreement is notable in view of the differences in procedures employed by the investigators to determine da/dN, the limited evidence from which estimates of $\bar{l}$ were made in several instances, and differences in texture among the various materials. It is also worth emphasizing that in view of the wide array of heat treatments and associated microstructural types represented in Table 1, this grain-size effect appears independent of microstructural morphology (e.g., the equiaxed α-grain structure associated with the RA vs. the Widmanstätten α associated with the BA -- cf. Fig. 1, in particular).

Secondly, it is apparent that in those cases where microstructural modification of a given alloy has served to reduce da/dN, the reduction appears attributable to an increase in $\bar{l}$. The data from Amateau et al. [3] and Thompson et al. [10] well illustrate this point in both Figs. 1 and 2. In the case of the Ti-6Al-4V alloy of Thompson et al. [10], it is clear that the microstructural modifications affected by the different heat treatments (STOA, RA and BA) serve to reduce da/dN as the consequence of an increase in $\bar{l}$. Similarly in the case of the Ti-6Al-6V-2Sn alloy of Amateau et al. [3], microstructural modifications affected by the different heat treatments (MA, DA and BA) serve to reduce da/dN, apparently as the result of an increase in $\bar{l}$. Interestingly, however, Eylon and Pierce [5] found a negligible change in da/dN with microstructural modification in a Ti-6Al-4V alloy -- apparently as the consequence of an insignificant change in $\bar{l}$ associated with their heat treatments, as indicated in Figs. 1 and 2.

Thirdly, when the collective growth-rate data bands from Figs. 1-3 are compared for ΔK levels of 15, 21 and 40 MPa$\sqrt{m}$ -- as illustrated in Fig. 4, it is apparent that the dependence of da/dN on $\bar{l}$ diminishes as ΔK is increased. This diminution of the grain-size effect is interpreted as the consequence of a reduced portion of the structure-sensitive mode of crack growth that occurs with increased ΔK -- as will be discussed shortly.

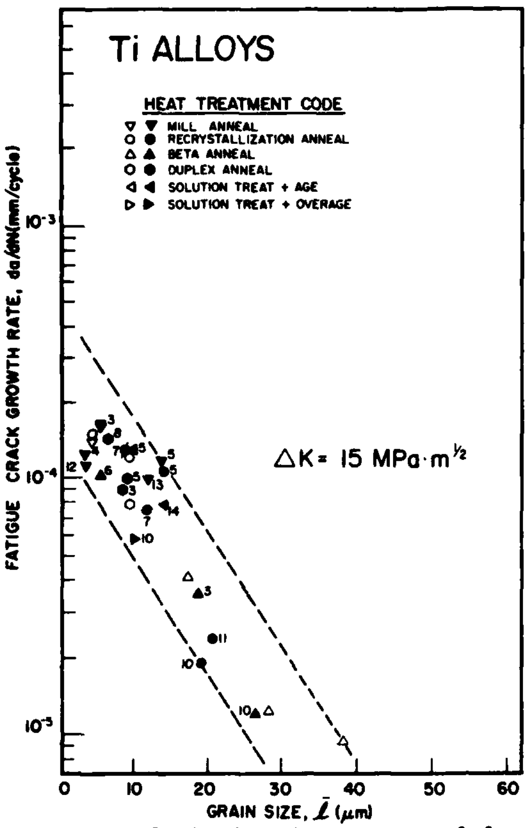

Fig. 1 - Grain-size dependence of fatigue crack growth rate, at ΔK = 15 MPa$\sqrt{m}$.

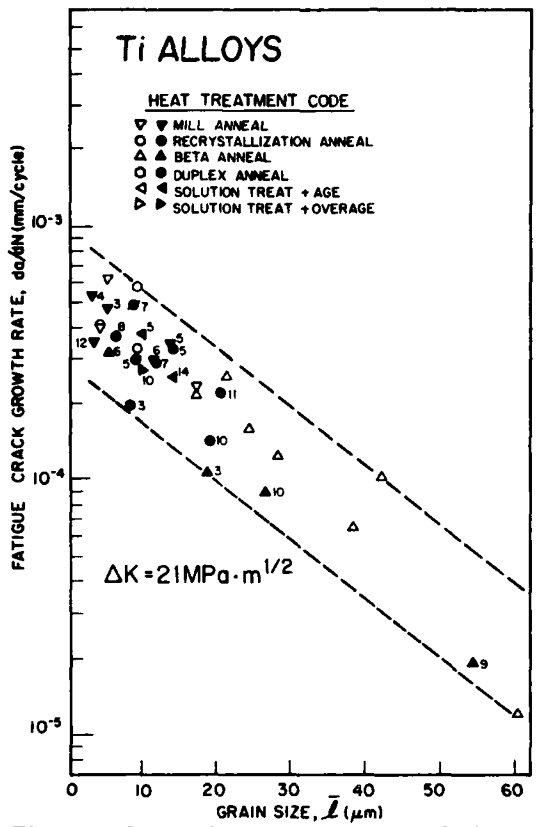

Fig. 2 - Grain-size dependence of fatigue crack growth rate, at ΔK = 21 MPa$\sqrt{m}$.

Discussion

The grain-size effect and its diminution with increased ΔK can be comprehensively interpreted in terms of the reversed (cyclic) plastic zone size model [16,17], by making use of principles which have emerged from our own in-depth studies of fatigue crack growth behavior in the Widmanstätten class of microstructures in $\alpha + \beta$ titanium alloys [1,2] -- as well as other observations. The picture that develops begins as follows:

If region-II crack growth rate data for an $\alpha + \beta$ titanium alloy (of arbitrary microstructure) are obtained over a sufficiently wide spectrum of ΔK levels, it appears that the logarithmic plot of da/dN vs. ΔK exhibits a bilinear form [1,2,10]. That is, as illustrated schematically in Fig. 5, there are two distinct branches that independently obey the power law [18],

$$da/dN = C\,(\Delta K)^m \tag{1}$$

and which join together at the transition point (T). In the hypotransitional region where the reversed plastic zone size (sketched for plane strain conditions) is less than the grain size, $r_y^c < \bar{\ell}$, a microstructurally sensitive (or "structure-sensitive") mode of crack growth occurs that involves crystallographic bifurcation in grains adjacent to the Mode I crack plane. This bifurcation causes a reduction in the effective ΔK and consequently da/dN, and thus the appearance of the transition itself. By contrast, in the hypertransitional region where $r_y^c > \bar{\ell}$, the grains within the larger r_y^c must necessarily deform as a continuum, which results in a microstructurally insensitive,

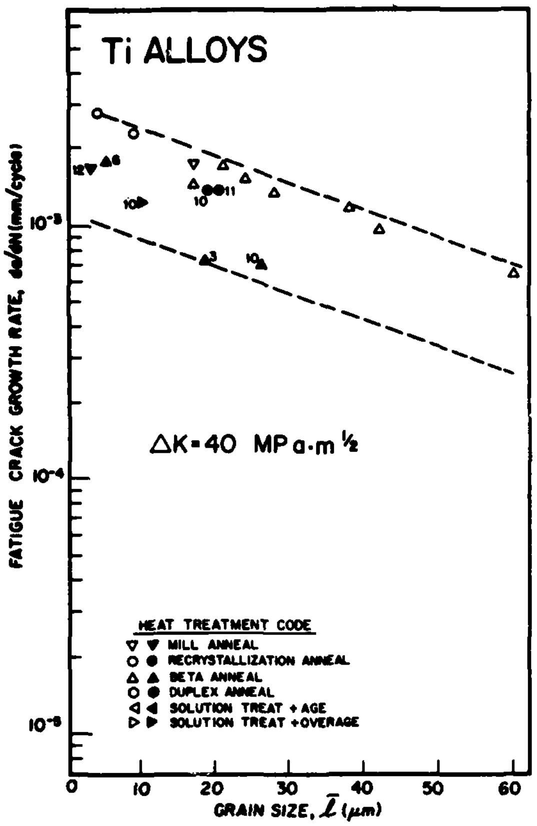

Fig. 3 - Grain-size dependence of fatigue crack growth rate, at $\Delta K = 40$ MPa$\sqrt{m}$.

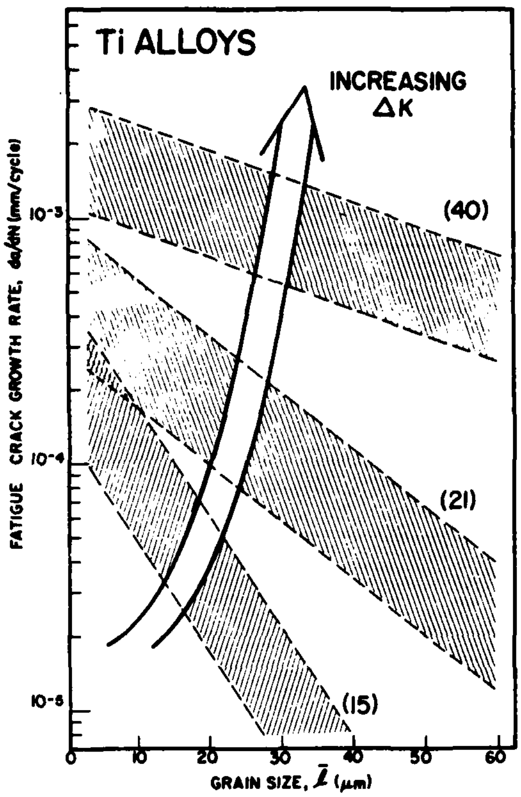

Fig. 4 - Diminution of grain-size effect on fatigue crack growth rate with increased stress-intensity range, ΔK (MPa$\sqrt{m}$).

nonbifurcated mode of crack growth [2,19]. It should be noted that bifurcation has been observed in the microstructurally sensitive region for a wide range of microstructures [20]. Moreover, it is appropriate to mention that Wanhill and Döker [13] have observed a difference in the dislocation substructures associated with the structure-sensitive and structure-insensitive modes of crack growth.

The inverse dependence of fatigue crack growth rates upon grain size appears directly attributable to this microstructurally sensitive mode of crack growth -- since larger bifurcated cracks (thought to be slip-band cracks [19]) occur as the grain size is increased, thus dispersing the strain-field energy of the macroscopic crack over increased volumes of material in the crack-tip region -- to further reduce the effective ΔK and consequently, da/dN. Quantitatively, a grain-size shift in the fatigue crack growth rate curve can be predicted, since the transition point (T) in Fig. 5 has been identified as the point at which the reversed plastic zone size [21],

$$r_y^c = 0.033\,(\Delta K/\sigma_y)^2 \qquad (2)$$

attains the <u>mean</u> grain size [2,19,22]. Thus at the transition point, where $r_y^c = \bar{l}$, it follows that

$$\Delta K_T = 5.5\,\sigma_y \sqrt{\bar{l}} \qquad (3)$$

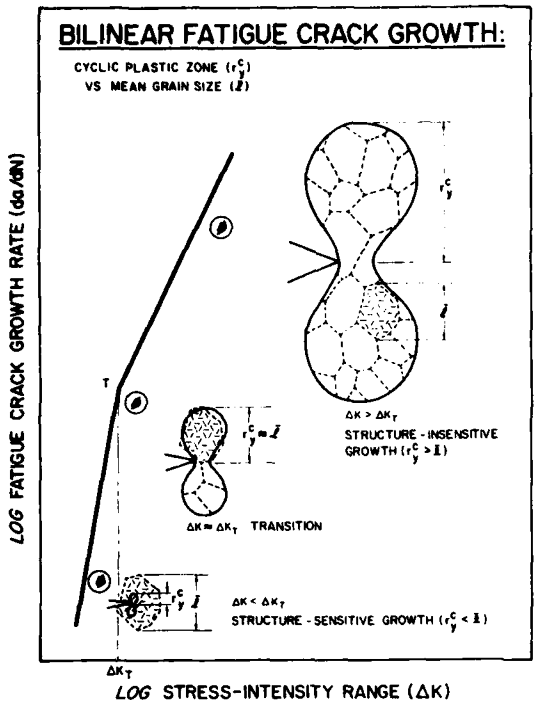

Fig. 5 - Effect of cyclic (reversed) plastic zone size, relative to grain size, upon development of bilinear form of fatigue crack growth behavior. Note transition from structure-sensitive mode of crack growth in lower branch to structure-insensitive mode in upper branch.

This shift in the da/dN data plot, as sketched in Fig. 6, is well documented for Widmanstätten microstructures [2], with significant evidence available for other microstructural types as well [10,22,23].

To further explain aspects of the illustration in Fig. 6 (viz., as concerns the differential in growth rates observed between points X and Y of the two curves, which occurs at a ΔK level that is hypertransitional in the case of both) -- and ultimately, to explain the diminution of the grain-size effect with increased ΔK, it is necessary to move beyond consideration of the mean grain size to focus upon a material's grain-size distribution as a whole, relative to the appearance of the bifurcated, microstructurally sensitive mode of fatigue crack growth. For grains in excess of the mean size, $l > \bar{l}$, a necessary requirement for the structure-sensitive mode of crack growth to occur is that $l > r_y^c$. Thus, even in the hypertransitional region II.b in Fig. 6, a remnant of structure-sensitive crack growth can arise in those grains that meet the condition:

$$l > r_y^c > \bar{l} \tag{4}$$

With regard to Fig. 6, the differential in growth rates between points X and Y is attributable to this remnant. In the case of the larger grained alloy, the bifurcations in this remnant are the larger, thus leading to the lower growth rate at point Y. Also contributing to the lower growth rate at point Y is the fact that the alloy of larger $\bar{l}$ contains a larger remnant of structure-sensitive growth (i.e., more grains meeting the condition expressed in (4)), by virtue of the closer proximity of point Y to the transition point, as compared to point X relative to the transition point of the other alloy. This assumes that all other aspects of the two alloys are the same -- including the degree of clustering (γ) of the grain-size distribution about its mean value [2],

$$\gamma = (l^{0.95} - \bar{l})^{-1} \tag{5}$$

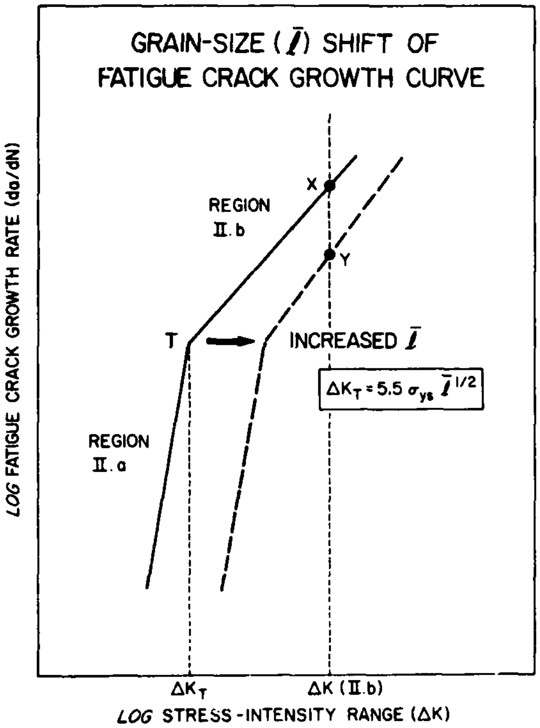

Fig. 6 - Shift of the bilinear crack growth rate plot with increased grain size.

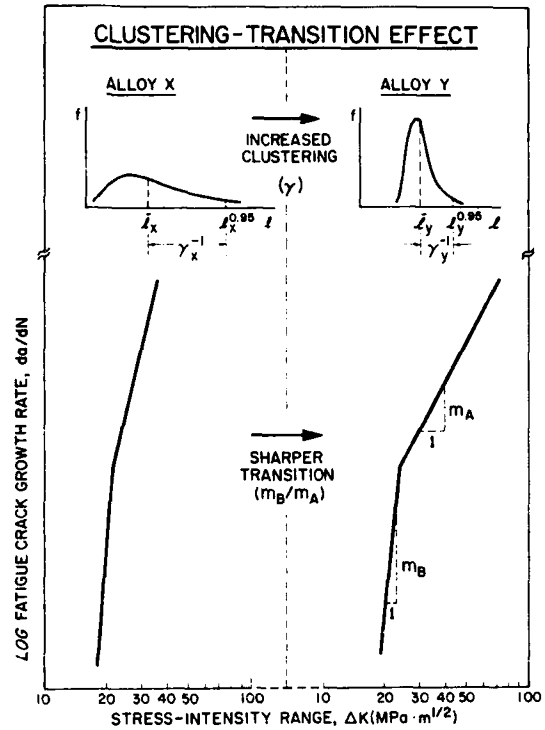

Fig. 7 - Influence of clustering of grain-size distribution (cf. histograms at top) on sharpness of transition (cf. growth-rate plots at bottom).

where $\ell^{0.95}$ is the grain size from the 95th percentile of the distribution, as illustrated schematically in the grain-size histogram for alloys X and Y at the top of Fig. 7. As γ increases, it has been shown that the hypertransitional slope (cf. Figs. 5-7) decreases and the transition is significantly sharpened [2] as illustrated in Fig. 7, since any remnant of the structure-sensitive, bifurcated mode of crack growth is reduced.

Now it is appropriate to address the diminution of the grain-size effect with increased ΔK. First of all, consider the grain-size histogram for a given alloy in relation to the cyclic (reversed) plastic zone size generated at different points along the fatigue crack growth rate plot, as illustrated in Fig. 8 -- where points A, T and B could perhaps represent ΔK levels of 15, 21 and 40 MPa$\sqrt{m}$, respectively. Then at any of these points, the grains which contribute to the structure-sensitive mode of crack growth must meet the condition, $\ell > r_y^c$. As shown in Fig. 9, as ΔK increases from point A to T, to B (top to bottom of figure), the portion of grains that meet this condition is diminished -- as represented by the shaded portions of the histograms at the respective points. Thus diminution of the grain-size effect results from a decreased portion of the structure-sensitive mode of crack growth as ΔK increases (since differentials in da/dN between different alloys arise from only this mode, and not the structure-insensitive mode). Or, put another way: If the differential in da/dN between two alloys is considered as ΔK is increased to higher levels, such as that illustrated by points X and Y in Fig. 6, then it can be said that the differential in da/dN will tend to vanish as the portion of structure-sensitive crack growth approaches negligible levels (as suggested in Fig. 9 for point B) -- even though values of $\bar{\ell}$ for the two alloys considered may be quite different.

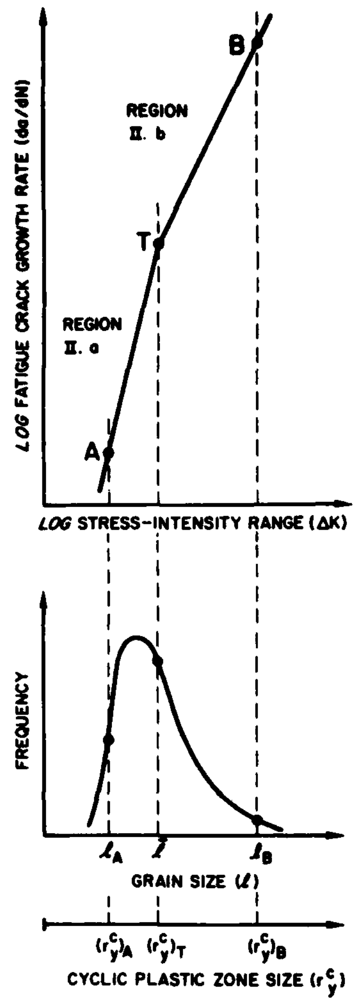

Fig. 8 - Comparison of cyclic (reversed) plastic zone size associated with different points, A, T and B on the crack growth rate plot to size of alloy grains shown in grain-size histogram.

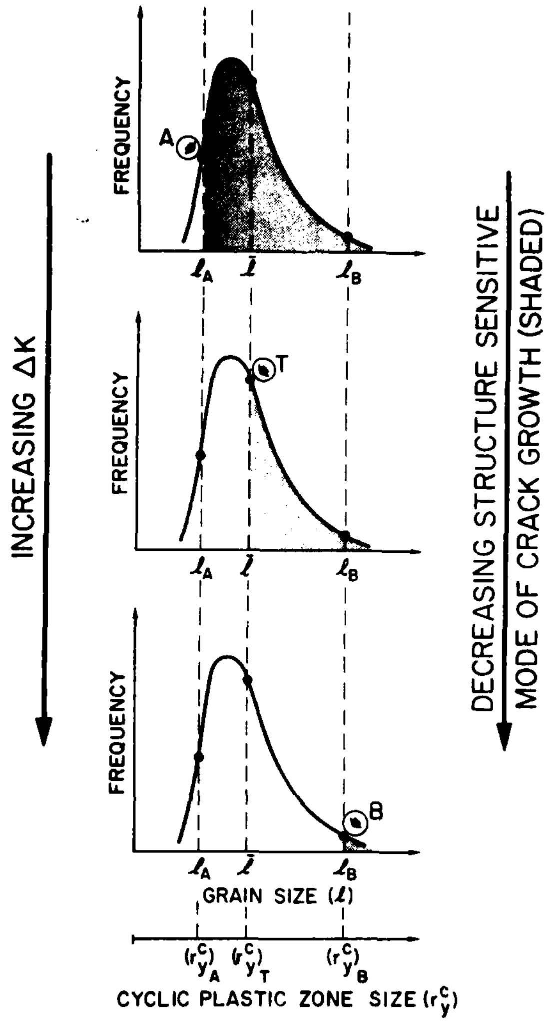

Fig. 9 - Decrease in portion of grains that contribute to structure-sensitive mode of crack growth (shaded portion of grain-size histograms) at points A, T and B (cf. companion plot in Fig. 8).

Conclusions

1. Results obtained through analysis of the literature agree with those of our own as regards the effect of grain size on region-II fatigue crack growth rates of $\alpha + \beta$ titanium alloys in ambient air, viz. that for a given value of ΔK, da/dN decreases as $\bar{\ell}$ is increased.

2. The analysis indicates that when microstructural modification of a given alloy affects a reduction in da/dN, the reduction appears attributable to an increase in $\bar{\ell}$; conversely, when microstructural modification fails to affect a significant change in da/dN, the result appears attributable to a negligible change in $\bar{\ell}$.

3. Comparison of fatigue crack growth behavior at stress-intensity ranges of 15, 21 and 40 MPa$\sqrt{m}$ indicates a diminution of the grain-size effect with increased ΔK.

4. As elucidated in terms of the reversed plastic zone size model, diminution of the grain-size effect follows as a consequence of the reduced portion of the structure-sensitive mode of crack growth present as ΔK is increased.

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